



**HAL**  
open science

## Middle-Atmosphere Temperature Monitoring Addressed with a Constellation of CubeSats dedicated to Climate issues

Philippe Keckhut, Alain Hauchecorne, Mustapha Meftah, Sergey Khaykin, Chantal Claud, Pierre Simoneau

### ► To cite this version:

Philippe Keckhut, Alain Hauchecorne, Mustapha Meftah, Sergey Khaykin, Chantal Claud, et al.. Middle-Atmosphere Temperature Monitoring Addressed with a Constellation of CubeSats dedicated to Climate issues. *Journal of Atmospheric and Oceanic Technology*, 2021, 38 (3), pp.685-693. 10.1175/JTECH-D-20-0046.1 . insu-03136030v2

**HAL Id: insu-03136030**

**<https://insu.hal.science/insu-03136030v2>**

Submitted on 6 Jan 2023

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

## **Middle-Atmosphere Temperature Monitoring Addressed with a Constellation of Cube-Sats dedicated to Climate issues**

PHILIPPE KECKHUT\*, ALAIN HAUCHECORNE, MUSTAPHA MEFTAH, SERGEY KHAYKIN

*LATMOS/IPSL, UVSQ, Université Paris-Saclay, Sorbonne Université, CNRS/INSU, Guyancourt, France*

CHANTAL CLAUD

*Laboratoire de Météorologie Dynamique, Ecole Polytechnique, CNRS/INSU, Palaiseau, France*

PIERRE SIMONEAU

*ONERA, Chemin de la Hunière, Palaiseau, France*

### ABSTRACT

While meteorological numerical models extend upward to the mesopause, mesospheric observations are required for leading simulations and numerical weather forecasts and climate projections. This work reviews some of the challenges about temperature observation requirements and the limiting factors of the actual measurements associated with atmospheric tides. A new strategy is described here using the limb scattering technique based on previous experiments in space. Such observations can be placed on board cube-satellites. Technical issues are the large dynamic range (3 magnitudes) required for the measurements, the accuracy of the limb pointing and the level of stray light. The technique described here will expect accuracy of 1-2 K with a vertical resolution of 1-2 km. A constellation of 100 platforms will allow to provide temperature observations with space (100 km) and time resolution (3 hours) recommended by the World Organization Meteorology, while tidal issues could be resolved with a minimum of 3-5 platforms with specific orbit maintained to avoid drifts.

### 1. Introduction

The middle atmosphere (MA) is under the conjugated influence of climate changes, due to anthropogenic activities and natural variability. This region exhibits variability on time and space with scales ranging from thousands of kilometers to tens of meters and extending in the different atmospheric layers from troposphere up to the lower thermosphere. It includes the MA which extends from the tropopause (10-15 km) to the turbopause (100-105 km) comprising the stratosphere and mesosphere. The stratosphere (12-50 km) was extensively studied because of the ozone hole discovery (Farman et al. 1985) and the associated cooling due to the strong temperature-ozone dependence in the upper stratosphere. The increase of GHGs (Green House Gases) induces a global warming at the surface and in the troposphere but also a global cooling in the MA due to the thermal infrared radiation emitted by GHGs escaping directly to the space because of the low optical thickness of the atmosphere above. However, full interactive numerical models including the MA have only appeared since the 1990s (Rind et al. 1990). The Coupled Model Inter-comparison Project reveal that models that do not represent the upper atmosphere present biases in the representation of stratospheric climate and variability

(Charlton-Perez et al. 2013). For this reason, the European Center for Medium range Weather Forecast (ECMWF) extends meteorological analyses up to the mesopause (80 km). However, comparisons between meteorological analyses and ground-based instrument reveal large bias (Le Pichon et al. 2015; Wright and Hindley 2018) that are due to a critical lack of observation above the stratopause and a crude gravity wave parametrization. Long-term temperature evolutions in the mesosphere (Beig et al. 2003) also suffer from the lack of observations (section 2). However limb viewing observations allows temperature retrieval with a good vertical resolution and can be deployed on small satellites (section 3). An issue is related to the fact that temperature observations exhibit strong interferences with tides as described in section 4. The concept of constellation of several cubesats as described in section 5 could be an interesting approach to provide unbiased mesospheric temperature fields for models. Section 6 will provide conclusions about such perspectives.

### 2. Middle Atmosphere Temperature Variability

Systematic global temperature observations from space were initiated since September 1978 with the SSU (Stratospheric Sounding Unit) onboard the successive NOAA operational satellite (Gelman and Nagatani 1977). After adjustments with rockets (Gelman et al. 1986) continuous

---

\*Corresponding author: Philippe Keckhut, keckhut@latmos.ipsl.fr

temperature series were derived by the U.S. National Centers for Environmental Prediction (NCEP), and decadal temperature trends were estimated (Hood et al. 1993; Lambeth and Callis 1994) with large uncertainties due to adjustment uncertainties between the successive satellites (Wild et al. 1995). The updated temperature series by two different groups show that derived trends exhibit larger differences between both of them than with temperature series provided by numerical models (Thompson et al. 2012) and finally provide a better agreement on zonal series (Maycock et al. 2018). A new generation of stratospheric temperature sounders were obtained with the Advanced Microwave Sounding Unit (AMSU) on board successive NOAA satellites. The overlap periods reveal bias and drifts (Keckhut et al. 2015) in agreement with tidal models indicating that most of the observed drifts are likely due to the atmospheric tides. Atmospheric tides are caused by a combined effect of ozone and water vapor photodissociation (Haefele et al. 2008) and insolation absorption by these same species, inducing waves with periods of 24 hours and associated harmonics on dynamical parameters (temperature, wind and pressure) that propagate in the whole atmosphere (Chapman and Lindzen 1970). The difficulties about time continuity on both SSU and AMSU series are mainly due to the combined effects of satellite orbit, atmospheric tides, and differences in weighting functions (Figure 1). With temperatures from the AQUA/AMSU instrument having an orbit maintained, more accurate trends can be obtained (Funatsu et al. 2016; Khaykin et al. 2017). While trend analyses are very sensitive to time and space sampling (Funatsu et al. 2011), observations will benefit from sampling more than one solar time while tides may also differ due to climate change (Morel et al. 2004). AMSU has a finer vertical resolution than SSU but sounds not as high as SSU (Zou and Qian 2016). Mesospheric temperature was first investigated by rocketsondes operated systematically since the 1960's up to the end of the 1980's. Since then, observations have been performed with lidars within the NDSC network (Kurylo 1991) at several sites from tropics to poles. In the upper mesosphere temperature data are also obtained from airglow OH spectrometers (Bittner et al. 2002). In addition, few other research instruments have provided multi-years temperature data, and trends have been derived by several groups (Beig et al. 2003). These observations are consolidated and coordinated through the ARISE project (Blanc et al. 2017). No operational satellites are dedicated to provide systematic mesospheric temperatures. Some research satellites like the HALOE experiment aboard UARS provide multi-year observations using the solar occultation technique (Remsberg et al. 2002) with a good vertical resolution. However, no successive similar instruments were planned to be launched soon to insure the continuity. At that time only two research satellites provide temperature in the mesosphere: MLS (Microwave Limb Sounder)

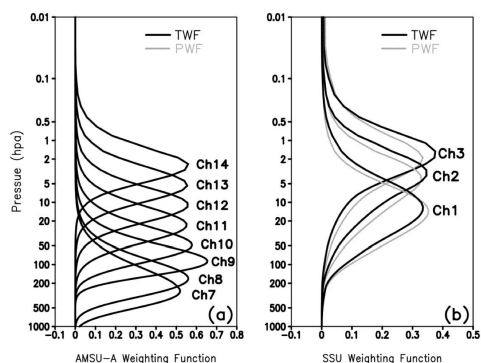


FIG. 1. Vertical weighting functions for AMSU channels 7 to 14 and for SSU from channels 1 to 3. Weighting functions estimated with Planck functions are indicated in gray (Zou and Qian 2016).

on board AURA/NASA and SABER (Sounding of the Atmosphere using Broadband Emission Radiometry) on board TIMED/NASA (Thermosphere Ionosphere Mesosphere Energetics Dynamics). Large bias with ground-based observations are reported (Wing et al. 2018), and no similar follow-up missions are planned. Microwave instruments like MLS do not exhibit a good vertical resolution, and are then not sensitive to disturbances like mesospheric inversions. Instruments like SABER providing more information in the mesosphere/thermosphere region and display strong sensitivity to atmospheric tides. In the MA, short scale processes like gravity waves are fundamental to understand atmospheric evolution like sudden stratospheric Warmings (Hauchecorne et al. 2019a; Noguchi et al. 2020) and cannot be vertically resolved by operational sensors (Figure 1). Comparison with numerical weather model shows that under 10 days part of the observed variability is not included in meteorological analyses (Le Pichon et al. 2015). The variability in the mesosphere is also due to gravity waves breaking leading to mesospheric inversions of several tenths of degrees within a vertical layer of 10-20 km (Hauchecorne et al. 1987). Such structures are already observed from space (Leblanc et al. 1995) and modelled (Hauchecorne and Maillard 1990) and were detected also by GOMOS (Hauchecorne et al. 2019a). The role of the mesospheric and upper stratospheric circulations appear to be critical on the onset and development of SSWs (Charlton-Perez et al. 2013).

The observation requirements are compiled by World Meteorological Organization (WMO) through the Observing Systems Capability Analysis and Review Tool (OSCAR: [www.wmo-sat.info/oscar](http://www.wmo-sat.info/oscar)). The target resolutions correspond to 50-100 km and 3-6 hours time-resolution with an accuracy of 1-2 K.



Fig. 2. Limb view showing the blue scattering induced by molecules illuminated by the sun light, the dark part above corresponding to the atmosphere, white part below corresponding to cloud and aerosols scattering (Courtesy NASA-JSC Gateway to Astronaut Photography of Earth, Image STS073-E5113).

### 3. Limb viewing measurements from small satellites

The scattering of sunlight is only due to atmospheric molecules above the aerosol stratospheric layer (25-30 km) and when no high-altitude polar clouds are present (Polar Stratospheric or Mesospheric Clouds). Since Lord Rayleigh, the scattering is known to have a higher efficiency for the shorter wavelengths revealing a blue scattering (Figure 2). This scattering is directly proportional to the atmospheric density.

Thus, similarly to the lidar technique (Hauchecorne and Chanin 1980), temperature can be retrieved by downward integration of the hydrostatic equation assuming the atmosphere follows the perfect gas law. The initialization is performed at the top of the profile assuming that the temperature is close to the climatology. The associated uncertainty is decreasing rapidly with altitude because the density itself increases sharply and the error becomes rapidly negligible providing an unbiased absolute temperature profile in the whole MA. This method has been first applied from space on bright limb using the Solar Mesosphere Explorer (Clancy et al. 1994). The similar retrieval was applied on space experiments that were not initially planned to provide temperatures like WINDII on UARS (Shepherd et al. 2001), Osiris on Odin (Sheese et al. 2012) and more recently with GOMOS on ENVISAT (Hauchecorne et al. 2019b) but having a limb viewing geometry. The temperature retrievals were validated by ground-based instruments showing very accurate unprecedented observations in the mesosphere with good vertical resolution. While existing instrument in space shows great capabilities, the development of a dedicated instrument appears to be feasible as it could be integrated on a small platform. Similar strategies have already been proposed for Earth radiative balance

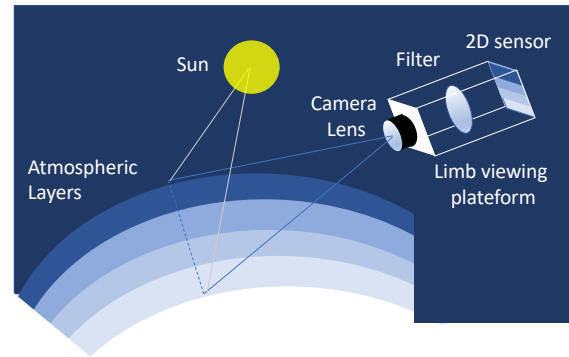


Fig. 3. Schematic instrumental setup for limb viewing geometry from space.

(Meftah et al. 2020) for other essential climate variables. Such instrument requires to observe the bright limb, and make the image of the Limb (Figure 3) on a CCD sensor. The main difficulties consist in:

- tracking the limb with a good accuracy,
- being sensitive to a large dynamic signal while density is decreasing by two magnitudes from 30-80 km and
- fully eliminating parasite lights from Earth surface and internal glint.

To achieve a vertical resolution of 1 km and an accuracy of 1 K, an accuracy better than 200 meters is required as the mean temperature gradient in the mesosphere corresponds to 4K/km. For the pointing, if we consider a satellite cruise altitude of 600 km and a tangent altitude at 65 km above the surface, the distance to the limb is 2678 km. An accuracy of 200 meters corresponds to 70 microradians (or 15 arc-sec). With Gomos such accuracy was insured with a star tracker (Bertaux et al. 2010). If such device cannot be used, the altitude can be derived from the image of the horizon observed on the full multi-point detector. Such concept avoids to scan the limb in order to retrieve the density profile with a mechanic system and provide an altitude reference in detecting the Earth horizon. The main challenge with such detector consists in providing enough sensitivity with a small noise level, over a signal range covering more than 3 magnitudes (Figure 4). Multi-point detectors exhibit different characteristics in terms of sensitivity response and noise level as observed on Gomos detector (Keckhut et al. 2010), and requires an accurate calibration as performed on the GOMOS instrument (Kyrola et al. 2010).

Another important issue is related to the noise induced by the external stray light reaching the detector. It appears that some light outside the nominal field of view of the

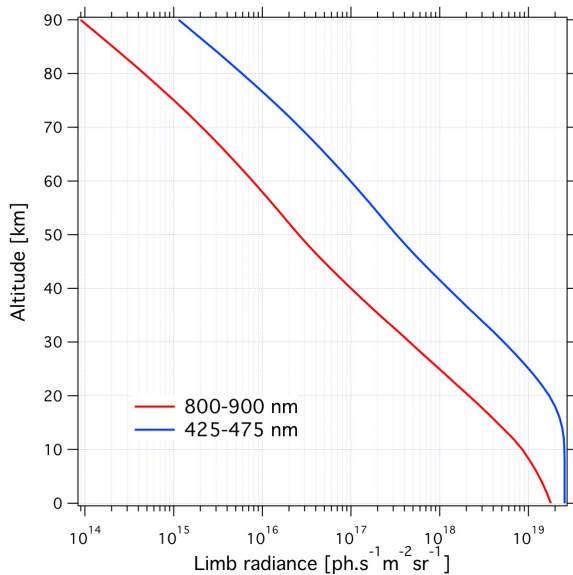


FIG. 4. Simulated limb radiance emission due to Rayleigh scattering in the visible domain (425-475 nm) and near InfraRed domain (800-900 nm)

instrument was observed on the Gomos instrument (Figure 5) analyses on Envisat (Kyrola et al. 2010). Such noise reduce the altitude range. Part of the light can be scattered by some platform hardware into the baffle and optics. The other part is coming from the sun-illuminated nadir. Noise can be estimated directly from signals coming from altitudes above 100 km, however capability will be increase if the noise effects could be reduced by the design of the instrument. The dynamic and level of noise will allow to select the correct 2D multi-pixel detector.

#### 4. Tidal issues

Atmospheric tidal theory has been proposed by Chapman and Lindzen (1970) predicting a zonally-invariant migrating mode (Sun-synchronous) and a zonally-variant non-migrating tide. The atmospheric tides are primarily induced by the daytime heating of stratospheric ozone layer and convective latent heat release in the upper troposphere, whereas the ozone and water vapor are themselves subject to a strong diurnal cycle due to the photodissociation effect (Haefele et al. 2008). Perturbations of thermodynamical dynamical parameters like temperature and wind propagate vertically throughout the different atmospheric layers up to the thermosphere, and their amplitudes grow with decreasing pressure due to energy conservation.

Until recently, only few observations of tides in the stratosphere were available. Tidal studies in this layer have

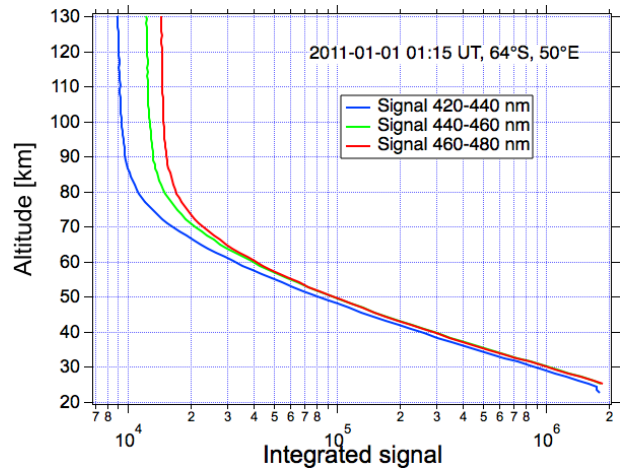


FIG. 5. Real observation performed by GOMOS/ENVISAT (noise detector) of the sunlight scattered by the Earth's limb in 3 spectral bands as a function of tangent altitude. From Hauchecorne et al. (2019b)

thus been restricted almost exclusively to rocket soundings. Rocket-borne temperature measurements had sparse diurnal coverage and were also prone to errors induced by radiation from exposed components of the rocketsonde (Finger and H.M. 1967; Hoxit and Henry 1973).

Atmospheric tides from satellite measurements have been obtained from LIMS (limb infrared monitor of the stratosphere) instrument aboard the Nimbus7 (Hitchman and Leovy 1985), ISAMS (improved stratospheric and mesospheric sounder) and MLS (microwave limb sounder) instruments aboard the upper atmosphere research satellite (Dudhia et al. 1993; Keckhut et al. 1996), and more recently from CRISTA mission (Ward et al. 1999; Oberheide and Gusev 2002). However, satellite radiometers need systematic validations and periodic calibrations by ground references and observations are impeded with low horizontal and vertical resolutions and a viewing window that limits the local time of observations. The analyses of daily-scale atmospheric fluctuations with associated for example with planetary waves are potentially contaminated by the non-migrating diurnal tides. The distortion in the analysis of planetary waves due to the tidal contamination was found to be of the same magnitude to the impact of noise in the data averaging over space and time (Zhang et al. 2006). The diurnal solar tide is one of the most prominent features in the middle atmosphere. While the tidal effect on large-scale stratospheric dynamics is small, its representation in a model is important for data assimilation in order to avoid introducing biases associated with the local time of the measurements (Swinbank and O'Neill 1994; Swinbank et al. 1999). This issue is much more critic in the mesosphere where the tidal amplitude is nearly a magnitude larger. Data processing from a single satellite requires

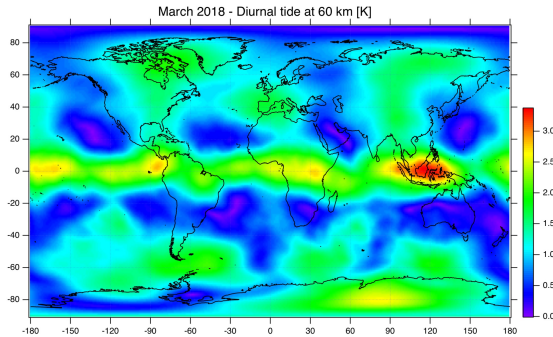


FIG. 6. Diurnal cycle derived from 6 hours ERA interim output average at 60 km over the month of March 2018.

large assumption about tidal characteristics (Huang et al. 2010). The tide is also modulated by ozone, water vapor density and by the dynamic (McLandress 2002), thus is sensitive to interannual changes like the QBO and SAO. Numerical simulations reveal a high sensitivity and expect tides characteristics to vary with climate changes (Morel et al. 2004). Thus simultaneous tidal estimates is required for assimilation or comparisons of any measurements performed at different time of the day. One shortcoming of the satellite mesospheric temperature data is that they are biased by the presence of migrating tides depending on the local times at which the daily zonal mean temperatures are obtained. For WINDII the diurnal tide contribution cannot be determined since these are only daytime observations. In the MLS and SABER cases, such determination requires different format of the data processing as it will take about 36 and 60 days, respectively, to obtain full 24-h local-time coverage. In this respect, it is helpful to consider the results of Forbes and Wu. (2006) on the retrieval of tidal parameters from the MLS temperature observations. This issue is a strong limitation for waves with period greater than 2 days, because of aliasing effects with this tidal periods. In the mesosphere, ERA interim model, which provides data every 6 hours, allows to derive a diurnal cycle in assuming no semidiurnal component and only a diurnal one (Figure 6). This calculation average over one month reveals at 60 km a large difference with latitude but also unexpected large differences along the longitude because of the strong presence of non-migrating tides. Complementary analyses with superDARN radar reveal a large variability of tides in wind with time and even over a single latitude (Hibbins et al. 2019).

## 5. Small-satellite strategy, stable orbit and constellations

The orbit needs to be selected to see an illuminated limb. In the summer hemisphere, above 30 km, a large portion of the diurnal cycle is concerned (more than 15 hours at  $45^\circ$  in latitude) while in the winter hemisphere a reduced portion is available (less than 10 hours at  $45^\circ$  in latitude). If most of the variability induced by atmospheric tides can be modelled by a diurnal and a semi-diurnal components, 5 unknown variables need to be considered (amplitude and phase for both waves and the mean). For example, for the August month, time evolution induced by tides are provided by the Global Wave Scale Model (Hagan 1999). If we consider a noise of 2K at 65 km at mid latitude (Leblanc et al. 1998) with 5 different solar times and 30 observations (corresponding to 1 month daily measurements), the tidal retrieval can be considered as perfect (figure 6). While the satellite has two solar time observations for respectively ascending and descending orbits, then only 3 satellites are necessary to retrieve atmospheric tides. During winter, the night is too long to provide a sufficient coverage to retrieve the full characteristic of tidal waves (Figure 7). In Figure 6, it can be clearly seen how important are the crucial observations at around 19:00 to retrieve the amplitude of tides. However the 3 solar-time observations are enough to retrieve the daylight portion of the temperature daytime evolution. One of the important issues to insure time continuity, consists in maintaining the orbit stable in time while a drift would induce change of the time of measurements. Due to the atmospheric tides inducing several-degrees temperature oscillations in the middle atmosphere, the drift about the revising time over a given location, will induce a temperature drift that could be interpreted either as anthropogenic trend or instrumental drift. As discussed in section 2, tides have been already observed with operational instruments like SSU (Wild et al. 1995) and AMSU (Keckhut et al. 2015) and were a severe limitation for trend estimates, unless the instruments have been installed on platforms with stable orbits (Funatsu et al. 2016).

However, such temporal sampling should be considered as a minimum requirement to address tidal issues. In order to achieve the required resolution provided by OS-CAR/WMO during daytime with Low Earth Orbit (LEO) satellites, 4 orbital planes with a 3-hours offset between them are needed, for example at 7:30, 10:30, 13:30 and 16:30 local time (Thompson et al. 2012). To achieve the horizontal resolution of 100 km for each orbit plane, 400 longitudes are needed at the equator. With up to 16 orbits per day for a LEO satellite, 25 platforms are needed on each orbit plane, corresponding to a total of 100 platforms.

## 6. Conclusions and recommendations

Previous studies have revealed difficulties to derive temperature trends in the upper stratosphere with successive

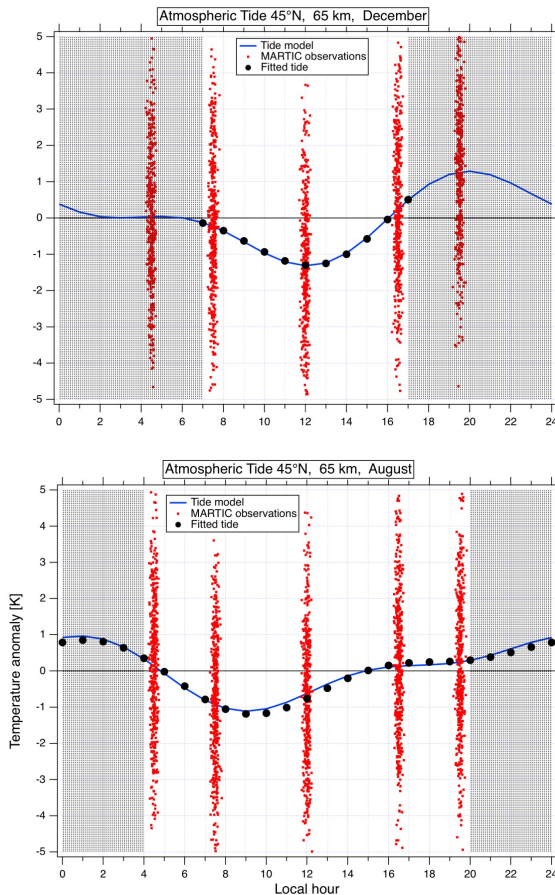


Fig. 7. Temperature anomalies estimated by the Global Scale Wave Model at 45°N at 65 km altitude for December (a) and August (b) in Blue. Red points correspond to 30 times a temperature composed by the model estimate and a random noise from a normal distribution with a standard width of 2 K for 5 different solar local times. Black dots correspond to the fitted curved including 2 waves of respectively 12 and 24 hours periods and a mean.

operational instruments with different orbits and/or having experienced orbit drifting in time due to tidal effects. Tidal issue is also limiting the assimilation processes in meteorological analyses. Moreover in mesosphere, where tidal amplitudes are much larger, temperature is only probed by few research satellites and requires a better observation strategy. To insure a good time temperature coverage of the upper stratosphere and mesosphere to avoid interferences with tides, several orbits are required, ideally more than 5 as shown by simulations described in section 5. Ideally, process studies would require around 100 platforms. This can not insure with traditional space platforms. While climate variables are linked together and is required to quantify

and understand the Earth imbalance, different constellations will be merged together with artificial intelligence methods. Temperature observations should be performed with a noise smaller than 1-2 Kelvin, and systematic bias even smaller by 2 magnitudes. Previous temperature retrievals from limb scattering appear to be one of the best technologies to provide accurate temperatures with a simple concept that can fit a small satellite platform, adequate for a constellation configuration of several cube-satellites. The design will need a viewing angle better than 70 microradians to insure a vertical resolution around 1 kilometer as required by WMO. Such constellation will be a perfect complement to ground observations deployed within the ARISE European infrastructure (Blanc et al. 2017) in construction.

**Data availability statement.** Atmospheric tide characteristics (amplitude and phase of the diurnal and semi-diurnal components) from the GSWM simulations are provided by Maura Hagan and can be downloaded freely on <http://www.hao.ucar.edu/modeling/gswm/gswm.html>. ERA Interim data used for estimating tidal changes can be obtained from <https://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=ml/>.

**Acknowledgments.** Authors thank Adrian Simmons for its support and useful discussions about the temperature requirements for ECMWF analyses.

## References

- Beig, G., and Coauthors, 2003: Review of mesospheric temperature trends. *Reviews of Geophysics - REV GEOPHYS*, **41**, doi:10.1029/2002RG000121.
- Bertaux, J.-L., and Coauthors, 2010: Global ozone monitoring by occultation of stars: an overview of gomos measurements on envisat. *Atmospheric Chemistry and Physics*, **10**, doi:10.5194/acp-10-12091-2010.
- Bittner, M., D. Offermann, H.-H. Graef, M. Donner, and K. Hamilton, 2002: An 18-year time series of oh rotational temperatures and middle atmosphere decadal variations. *Journal of Atmospheric and Solar-Terrestrial Physics*, **64**, 1147–1166, doi:10.1016/S1364-6826(02)00065-2.
- Blanc, E., and Coauthors, 2017: Toward an improved representation of middle atmospheric dynamics thanks to the arise project. *Surveys in Geophysics*, doi:10.1007/s10712-017-9444-0.
- Chapman, S., and R. Lindzen, 1970: *Atmospheric Tides*, Vol. 10. Springer, 106 pp.
- Charlton-Perez, A., and Coauthors, 2013: On the lack of stratospheric dynamical variability in low-top versions of the cmip5 models. *Journal of Geophysical Research: Atmospheres*, **118**, 2494D2505, doi:10.1002/jgrd.50125.
- Clancy, R., D. Rusch, and M. Callan, 1994: Temperature minima in the average thermal structure of the middle mesosphere (70 - 80 km) from analysis of 40- to 92-km sme global temperature profiles. *J. Geophys. Res.*, **99**, doi:10.1029/94JD01681.

- Dudhia, A., S. Smith, A. Wood, and F. Taylor, 1993: Diurnal and semidiurnal temperature variability of the middle atmosphere as observed by isams. *Geophys. Res. Lett.*, **20**, 1251–1254.
- Farman, J., B. Gardiner, and J. Shanklin, 1985: Large losses of total ozone in antarctica reveal seasonal clox/nox interaction. *Nature*, **315**, 207–210, doi:10.1038/315207a0.
- Finger, F., and W. H.M., 1967: Diurnal variation of temperature in the upper stratosphere as indicated by meteorological rocket experiment. *J. Atmos. Sci.*, **24**, 230–239.
- Forbes, J. M., and D. Wu., 2006: Solar tides as revealed by measurements of mesosphere temperature by the mls experiment on uars. *J. Atmos. Sci.*, **63**, 1776–1797.
- Funatsu, B., C. Claud, P. Keckhut, A. Hauchecorne, and T. Leblanc, 2016: Regional and seasonal stratospheric temperature trends in the last decade (2002–2014) from amsu observations: Stratospheric temperature trends. *Journal of Geophysical Research: Atmospheres*, doi:10.1002/2015JD024305.
- Funatsu, B., C. Claud, P. Keckhut, W. Steinbrecht, and A. Hauchecorne, 2011: Investigations of stratospheric temperature regional variability with lidar and advanced microwave sounding unit. *JOURNAL OF GEOPHYSICAL RESEARCH-ATMOSPHERES*, **116**, doi:10.1029/2010JD014974.
- Gelman, M., A. Miller, K. Johnson, and R. Nagatani, 1986: Detection of long-term trends in global stratospheric temperature from nmc analysis derived from noaa satellite data. *Adv. Space Res.*, **6**, 17–26.
- Gelman, M., and R. Nagatani, 1977: Objective analyses of height and temperature at the 5-, 2-, and 0.4 mb levels using meteorological rocketsonde and satellite radiation data. *Adv. Space Res.*, **XVII**, 117–122.
- Haeefe, A., and Coauthors, 2008: Diurnal changes in middle atmospheric h<sub>2</sub>o and o<sub>3</sub>: Observations in the alpine region and climate models. *Journal of Geophysical Research*, **113**, doi:10.1029/2008JD009892.
- Hagan, M., 1999: Gswm-98: Results for migrating solar tides. *Journal of Geophysical Research: Space Physics*, **104**, 6813–6827.
- Hauchecorne, A., and M.-L. Chanin, 1980: Density and temperature profiles obtained by lidar between 35 and 70 km. *Geophysical Research Letters - GEOPHYS RES LETT*, **7**, 565–568, doi:10.1029/GL007i008p00565.
- Hauchecorne, A., M.-L. Chanin, and R. Wilson, 1987: Mesospheric temperature inversion and gravity wave breaking. *Geophys. Res. Lett.*, **14**, 933–936, doi:10.1029/GL014i009p00933.
- Hauchecorne, A., S. Khaykin, P. Keckhut, N. Mze, G. Angot, and C. Claud, 2019a: *Recent dynamic studies on the middle atmosphere at mid- and low-latitudes using Rayleigh Lidar and other technologies*. Springer, 757 pp.
- Hauchecorne, A., and A. Maillard, 1990: A 2-d dynamical model of mesospheric temperature inversions in winter. *Geophysical Research Letters*, **17**, 2197–2200, doi:10.1029/GL017i012p02197.
- Hauchecorne, A., and Coauthors, 2019b: A new mesospheric dataset of temperature profiles from 35 to 85 km using rayleigh scattering at limb from gomos/envisat daytime observations. *Atmospheric Measurement Techniques*, 749–761, doi:10.5194/amt-12-749-2019.
- Hibbins, R., P. Espy, Y. Orsolini, V. Limpasuvan, and R. Barnes, 2019: Superdarn observations of semidiurnal tidal variability in the mlt and the response to sudden stratospheric warming events. *Journal of Geophysical Research*, **124**, 4862–4872, doi:10.1029/2018JD030157.
- Hitchman, M., and C. Leovy, 1985: Diurnal tide in the equatorial middle atmosphere as seen in lims temperature. *J. Atmos. Sci.*, **42**, 557–561.
- Hood, L., J. Jirikovic, and M. J.P., 1993: Quasi-decadal variability of the stratosphere - influence of long-term solar ultraviolet variations. *J. Atmos. Sci.*, 3941–3958.
- Hoxit, L., and R. Henry, 1973: Diurnal and annual temperature variation in the 30–60 km region as indicated by statistical analysis of rocket sonde temperature data. *J. Atmos. Sci.*, 922–933.
- Huang, F., R. McPeters, P. Bhartia, H. Mayr, S. Frith, J. Russell III, and M. Mlynczak, 2010: Temperature diurnal variations (migrating tides) in the stratosphere and lower mesosphere based on measurements from saber on timed. *Journal of Geophysical Research*, **115**, doi:10.1029/2009JD013698.
- Keckhut, P., B. Funatsu, C. Claud, and A. Hauchecorne, 2015: Tidal effects on stratospheric temperature series derived from successive advanced microwave sounding units. *Quarterly Journal of the Royal Meteorological Society*, doi:10.1002/qj.2368.
- Keckhut, P., and Coauthors, 1996: Semidiurnal and diurnal temperature tides (30–55 km): climatology and effect on uars-lidar data comparison. *J. Geophys. Res. (special issue on UARS Data Validation)*, **101**, 10 299–10 310.
- Keckhut, P., and Coauthors, 2010: Ozone monitoring with the gomos-envisat experiment version 5. *Atmospheric Chemistry and Physics Discussions*, **10**, doi:10.5194/acpd-10-14713-2010.
- Khaykin, S., and Coauthors, 2017: Post-millennium changes in stratospheric temperature consistently resolved by gps radio occultation and amsu observations: Temperature change from gps-ro and amsu. *Geophysical Research Letters*, doi:10.1002/2017GL074353.
- Kurylo, M., 1991: Network for the detection of stratospheric change (ndsc). *Proc. SPIE*, **1491**.
- Kyrola, E., and Coauthors, 2010: Retrieval of atmospheric parameters from gomos data. *ATMOSPHERIC CHEMISTRY AND PHYSICS*, doi:10.5194/acp-10-11881-2010.
- Lambeth, J. D., and L. Callis, 1994: Temperature variations in the middle and upper stratosphere: 1979–1992. *J. Geophys. Res.*, 20 701.
- Le Pichon, A., and Coauthors, 2015: Comparison of co-located independent ground-based middle-atmospheric wind and temperature measurements with numerical weather prediction models. *Journal of Geophysical Research Atmospheres*, **120**, doi:10.1002/2015JD023273.
- Leblanc, T., A. Hauchecorne, M.-L. Chanin, C. Rodgers, F. Taylor, and N. Livesey, 1995: Mesospheric temperature inversions as seen by isams (uars). *GEOPHYSICAL RESEARCH LETTERS*, **22**, 1485–1488, doi:10.1029/94GL03274.
- Leblanc, T., I. McDermid, A. Hauchecorne, and P. Keckhut, 1998: Temperature climatology of the middle atmosphere from long-term lidar measurements at mid- and low-latitudes. *GEOPHYSICAL RESEARCH LETTERS*, 17 191–17 204, doi:10.1117/12.319557.
- Maycock, A., and Coauthors, 2018: Revisiting the mystery of recent stratospheric temperature trends. *Geophysical Research Letters*, doi:10.1029/2018GL078035.



- McLandress, C., 2002: The seasonal variation of the propagating diurnal tide in the mesosphere and lower thermosphere. part ii: The role of tidal heating and zonal mean winds. *Journal of The Atmospheric Sciences - J ATMOS SCI*, **59**, 907–922, doi:10.1175/1520-0469(2002)059<0907:TSVOTP>2.0.CO;2.
- Meftah, M., and Coauthors, 2020: UVSQ-SAT, a Pathfinder CubeSat Mission for Observing Essential Climate Variables. *Remote Sensing*, **12** (1), art. 92 (24 p.), doi:10.3390/rs12010092, URL <https://hal-insu.archives-ouvertes.fr/insu-02424399>.
- Morel, B., P. Keckhut, H. Bencherif, A. Hauchecorne, G. Megie, and S. Baldy, 2004: Investigation of the tidal variations in a 3-d dynamics-chemistry-transport model of the middle atmosphere. *Journal of Atmospheric and Solar-Terrestrial Physics*, **66**, 251–265, doi:10.1016/j.jastp.2003.11.004.
- Noguchi, S., Y. Kuroda, H. Mukougawa, R. Mizuta, and C. Kobayashi, 2020: Impact of satellite observations on forecasting sudden stratospheric warmings. *Geophysical Research Letters*, e2019GL086233, doi:10.1029/2019GL086233.
- Oberheide, J., and O. Gusev, 2002: Observation of migrating and nonmigrating diurnal tides in the equatorial lower thermosphere. *Geophys. Res. Lett.*, doi:10.1029/2002GL016213.
- Remsberg, E., and Coauthors, 2002: An assessment of the quality of haloe temperature profiles in the mesosphere with rayleigh backscatter lidar and inflatable falling sphere measurements. *J. Geophys. Res.*, **107**, doi:10.129/2001jD001521.
- Rind, D., R. Suozzo, N. Balanchandra, and M. Prather, 1990: Climate change and the middle atmosphere: I, the doubled co2 climate. *J. Atmos. Sci.*, 475–494.
- Sheese, P., and Coauthors, 2012: Assessment of the quality of osiris mesospheric temperatures using satellite and ground-based measurements. *Atmospheric Measurement Techniques*, **5**, 2993–3006, doi:10.5194/amt-5-2993-2012.
- Shepherd, M., B. Reid, S. Zhang, B. Solheim, G. Shepherd, V. Wickwar, and J. Herron, 2001: Retrieval and validation of mesospheric temperatures from wind imaging interferometer observations. *Journal of Geophysical Research*, **106**, 24 813–24 830, doi:10.1029/2000JA000323.
- Swinbank, R., and A. O'Neill, 1994: A stratosphere-troposphere data assimilation system. *Monthly Weather Review - MON WEATHER REV*, **122**, doi:10.1175/1520-0493(1994)122<0686:ASTDAS>2.0.CO;2.
- Swinbank, R., R. Orris, and D. Wu, 1999: Stratospheric tides and data assimilation. *Journal of Geophysical Research*, **104**, 16 929–16 942, doi:10.1029/1999JD900108.
- Thompson, D., and Coauthors, 2012: The mystery of recent stratospheric temperature trends. *Nature*, **491**, 692–7, doi:10.1038/nature11579.
- Ward, W., J. Oberheide, M. Riese, P. Preusse, and D. Offermann, 1999: Tidal signatures in temperature data from crista 1 mission. *J. Geophys. Res.*, **104**, 16,391–16,403.
- Wild, J., and Coauthors, 1995: Comparison of stratospheric temperature from several lidars using nmc and mls data as transfer reference. *Geophysical Research Letters*, **100**, 11,105–11,111.
- Wing, R., A. Hauchecorne, P. Keckhut, S. Godin-Beekmann, S. Khaykin, and E. Mccullough, 2018: Lidar temperature series in the middle atmosphere as a reference data set D part 2: Assessment of temperature observations from mls/aura and saber/timed satellites. *Atmospheric Measurement Techniques*, **11**, 6703–6717, doi:10.5194/amt-11-6703-2018.
- Wright, C., and N. Hindley, 2018: How well do stratospheric re-analyses reproduce high-resolution satellite temperature measurements? *Atmospheric Chemistry and Physics*, **18**, 13 703–13 731, doi:10.5194/acp-18-13703-2018.
- Zhang, X., J. Forbes, M. Hagan, J. Russell III, S. Palo, C. Mertens, and M. Mlynczak, 2006: Monthly tidal temperatures 20-120 km from timed/saber. *Journal of Geophysical Research*, **111**, doi:10.1029/2005JA011504.
- Zou, C.-Z., and H. Qian, 2016: Stratospheric temperature climate data record from merged ssu and amsu-a observations. *Journal of Atmospheric and Oceanic Technology*, **33**, doi:10.1175/JTECH-D-16-0018.1.